AFFORESTATION FOR IMPROVING VALLEY URBAN AIR-QUALITY

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ABSTRACT

Lanzhou is one of the major cities in northwest China and the capital of Gansu Province and located at a narrow (2-8 km width), long (40-km), NW-SE oriented valley basin (elevation: 1,500- 1,600-m) with the Tibetan plateau in the west, Baita mountain (above 1,700-m elevation) in the north, and the Gaolan mountain in the south. Due to topographic and meteorological characteristics, Lanzhou is one of the most polluted cities in China. Meteorological conditions (low winds, stable stratification especially inversion), pollutant sources and sinks affect the air quality. Afforestation changes the mountain-valley local circulation system, destabilizes the atmosphere, and weakens the inversion. Besides, it may absorb some pollutants (sink). Lanzhou local government carried out afforestation and pollutant-source reduction (closing several heavy industrial factories) to improve the air-quality for the past two decades. Numerical model (RAMS-HYPACT) simulates the effect of afforestation on the air pollution control.

1. INTRODUCTION

Lanzhou is located at a narrow (2-8 km width), long (40-km), northwest-southeast oriented valley basin enclosed by 1,600-m elevation with the Tibetan plateau in the west, Baita mountain (above 1,700-m elevation) in the north, and the Gaolan mountain in the south (Fig. 1a). The highest elevation in the surroundings is the top of the Gaolan mountain around 2,150-m above the sea level.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**
4. TITLE AND SUBTITLE **Afforestation for Improving Valley Urban Air-Quality**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgruaduate School,Department of Oceanography,Monterey,CA,93943**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
A National Oceanographic Partnership Program Award . Third International Symposium on Air Quality Management, Istanbul, Turkey, 26-30 September 2005

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

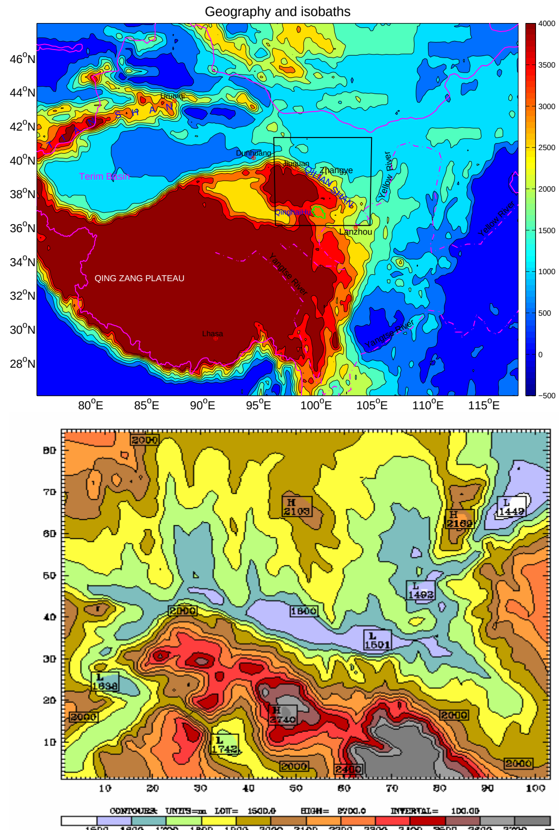

Fig. 1. Topography: (a) China, and (b) Great Lanzhou metropolitan area and surroundings.

Meteorological characteristics over the valley (great Lanzhou metropolitan) are semi-arid, weak wind, thick and strong inversion, which makes the low layer atmosphere very stable, low dispersion and causes severe air pollution (Fig. 2). Lanzhou is one of the most polluted cities in China. How can air pollution be effectively controlled in valley urban area? Two possible approaches can be adopted: (1) changing meteorological conditions (destabilizing atmosphere) and (2) reducing the pollution sources.

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Fig. 2. LANDSAT image.

2. SOME AIR-QUALITY IMPROVEMENT IN PAST DECADE

Since mid 1990s, the local Lanzhou government has conducted afforestation on the mountain slope and shut down several factories that emitted large amount of pollutants. The gaseous pollutants such as SO_2 and NO_x concentrations have been reduced. However, the particulate pollutants such as TSP and PM_{10} still keep high concentrations [Chu et al. 2004]. Fig. 2 shows the evolution of annual mean concentration for the three major pollutants (SO_2, NO_x, TSP) measured at the local environmental protection agency (EPA) station (103.631°E, 36.103°N), which is marked as the solid circle in Fig. 1b. The annual mean SO_2 has a maximum near 0.12 mg m^{-3} (above the third level standard: 0.10 mg m^{-3}) in 1994, and decreases monotonically to 0.055 mg m^{-3} (below the second level standard: 0.06 mg m^{-3}) in 2000 (Fig. 3a). The annual mean NO_x has two maxima (above the third level standard: 0.10 mg m^{-3}) in 1990 and 1995, and decreases monotonically to 0.05 mg m^{-3} (close to the second level standard: 0.05 mg m^{-3}) in 2000 (Fig. 3b). Except TSP, the air pollution (SO_2, NO_x) has been greatly improved.

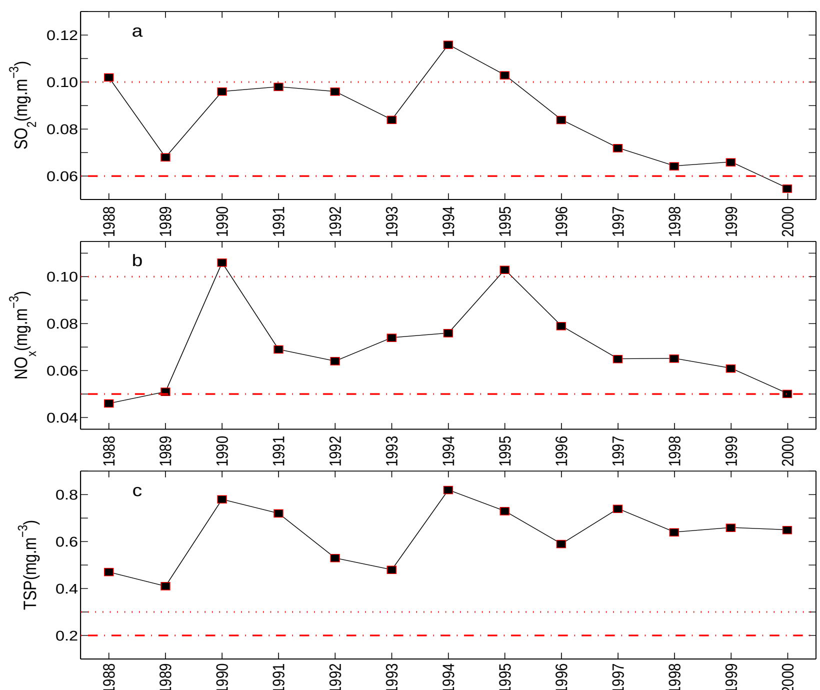

Figure 3. Annual mean concentration (mg m^{-3}): (a) SO_2, (b) NO_x, and (c) TSP measured at the local EPA station (103.631°E, 36.103°N), which is marked as the solid circle in Fig. 1b. The second-level standard is represented by the horizontal dash-dotted line and the third-level standard is represented by the horizontal dotted line.

3. MOUNTAIN-VALLEY CIRCULATION

Thermal heterogeneity of land surface can produce local circulations as strong as sea breezes (e.g., Chu 1987, Chu et al., 2005). Differential surface heating on the mountain slope generates local valley winds especially in winter or night (Fig. 4). The downward motion over the valley makes the atmosphere stable, and in turn weakens the diffusion of the pollutants.

Weakening this mountain-valley circulation (strong downward branch over the valley) destabilizes the atmosphere and enhances the diffusion rate. From physical point of view, reduction of surface thermal heterogeneity will weaken this circulation. Afforestation on the mountain slope may reduce the thermal heterogeneity and in turn improve the air-quality by atmospheric destabilization. Furthermore, the forest may also absorb pollutants (as pollutant sink). The Regional Atmospheric Modeling System (RAMS) is used to investigate this mechanism.

4. ATMOSPHERIC MODEL

4.1. Model Implementation

RAMS is a mesoscale modeling system including advanced model physics was developed by The Colorado State University. It is a community regional model widely used for numerical weather prediction, hydrological studies, and air quality studies. The nonhydrostatic RAMS is used in this study. The land surface model is coupled to RAMS to describe the effect of vegetation and interactive soil moisture on the surface-atmosphere exchange of momentum, heat, and moisture. This LSM is able to provide not only reasonable diurnal variations of surface heat fluxes as surface boundary conditions for coupled models, but also correct seasonal evolutions of soil moisture in the context of a long-term data assimilation system. Also, 1-km resolution vegetation and soil texture maps are introduced in the coupled RAMS-LSM system to help identify vegetation/water/soil characteristics at fine scales and capture the feedback of these land surface forcing. A monthly varying climatological $0.15^{\circ} \times 0.15^{\circ}$ green vegetation fraction is utilized to represent the annual control of vegetation on the surface evaporation.

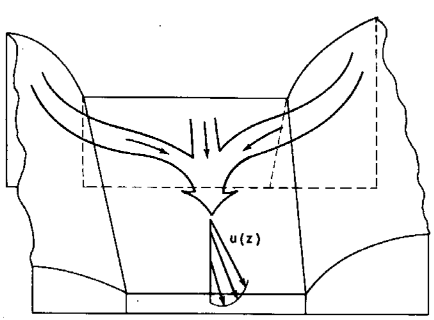

Fig. 4. Mountain-valley circulation.

LSM has one canopy layer and the following prognostic variables: soil moisture and temperature in the soil layers, water stored on the canopy, and snow stored on the ground. Four soil layers are used to capture the evolution of soil moisture and to mitigate the possible truncation error in discretization. The thickness of each soil layer from the ground surface to the bottom is 0.1, 0.3, 0.6 and 1.0 m. The precipitation is parameterized by several different schemes. Non-convective precipitation can be represented via an implicit scheme, whereby supersaturated water immediately precipitates, and an explicit scheme including prognostic equations for cloud- water and rainwater. Convective precipitation is parameterized via two cumulus convection schemes. We use the mass flux scheme, which accounts for the effects of penetrative downdrafts (Grell et al. 1994). In the numerical simulation, a flat bottom with elevation of 1460 m is assumed. This indicates that 850 hPa level is nearly at the land surface. Twenty-three vertical levels are used with 10 hPa at the top of the atmosphere. See the RAMS website: **http://www.rams.atmos.colostate.edu** for more information.

4.2. Triple-Nested Grid System

A triple-nested grid systems (Fig. 5) with the same center located at (35.1^{o}N, 103.8^{o}E) is used in this study. The first system (large) extends 720 km in the north-south direction and 540 km in the east-west direction with the grid spacing of 9 km. The second system (medium) extends 270 km in the north-south direction and 216 km in the east-west direction with the grid spacing of 3 km. The third system (small) extends 102 km in the north-south direction and 84 km in the east-west direction with the grid spacing of 1 km. Lanzhou is located in the smallest box. Roy and Avissar (2000) characterize the convective boundary layer (CBL) over domains with meso-gamma-scale (2-20 km) heterogeneity and find two typical length-scales of the processes when the length-scale of the heterogeneity exceeds 5-10 km: (a) 1.5 times the CBL height for turbulent thermals and (b) heterogeneity scale for organized eddies. Only the simulation in the smallest box is used for the analysis.

4.3. Boundary and Initial Conditions

At the surface, we use USGS vegetation 25-catogory with type-1 for urban/built-up land, and type-4 for mixed dry/irrigational plants (afforestation). The NCEP data along the lateral boundary (every 6 hours) of the largest box from December 1 to 31, 2000 are taken as the open boundary conditionOne way nesting is used for the triple-nested grid system. The larger model provides the lateral boundary conditions for the smaller model using a 5 point-buffer zone. The NCEP reanalysis data on December 1, 2000 are taken as the initial condition. The time step is 60 s for the first grid system, 30 s for the second grid system, and 10 s for the third grid system.

4.4. Numerical Experiments

Two numerical experiments are conducted: (1) with mountain-slope afforestation, and (2) without mountain-slope afforestation. The difference between the two is the land surface. The soil type on the mountain-slope is 4 for Exp-1 (Fig. 6) and 1 for Exp-2. Everything else is kept the same for the two experiments. Model difference (Exp-1 minus Exp-2) is analyzed especially the stratification and velocity field. Afforestation decreases the downward motion over the valley (i.e., reduction of the mountain-valley circulation) and stratification (destabilzation). The maximum reduction of the stratification is over the valley (-8°K/km). Such conditions favor the dispersion of valley urban air pollutants and improvement of the air-quality (Fig. 7).

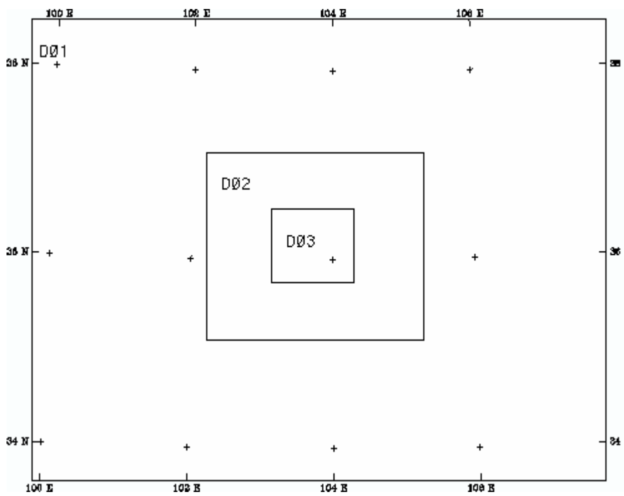

Fig. 5. Triple nesting grid system.

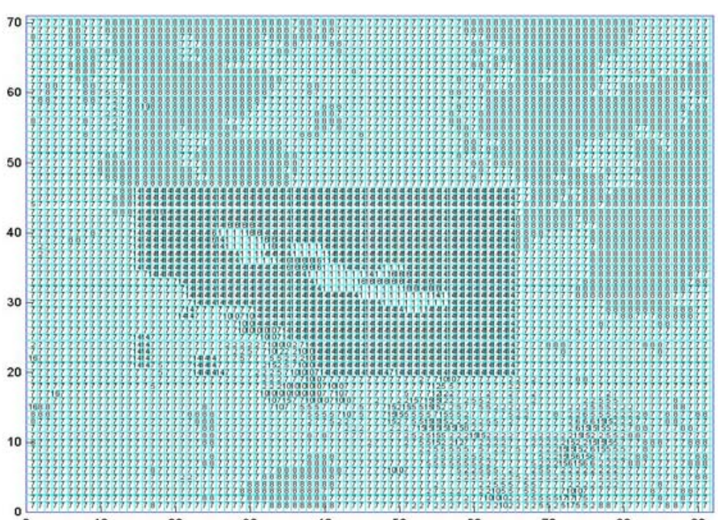

Fig. 6. Surface condition for mountain-slope afforestation with the soil type-4. The soil type-4 is replaced by type-1 for experiment without mountain-slope aforestation.

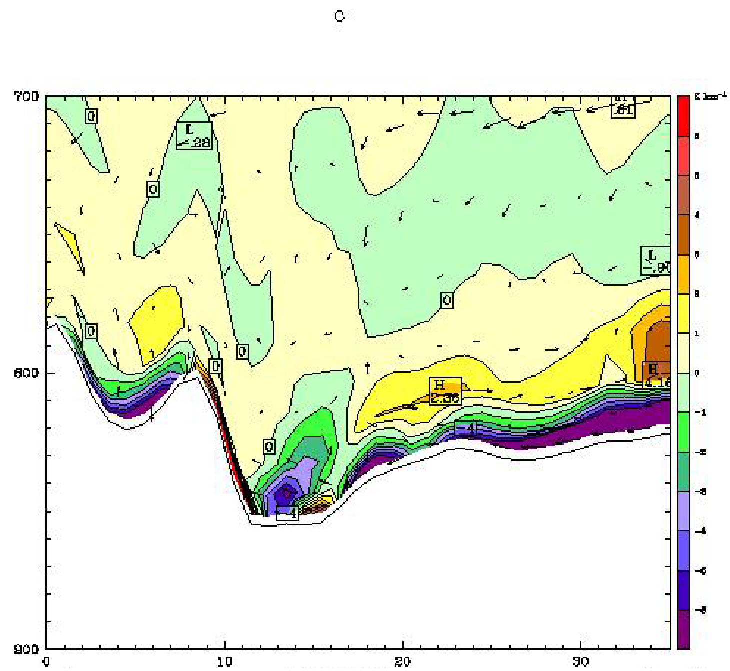

Fig. 7. Latitudinal cross-section along 103.8°E of differential (Exp-1 minus Exp-2) stratification (color contour) and (v, w) velocity vectors.

5. AIR POLLUTION MODEL

5.1. Model Description

The Hybrid Particle and Transport (HYPACT) model developed by the Mission Research Corporation (Walko et al., 2001) is used to predict the dispersion of air pollutants in 3-D, mesoscale, time dependent wind and turbulence field. HYPACT allows assessment of the impact of one or multiple sources emitted into highly complex local weather regimes, including mountain-valley and complex terrain flows. In this study, the modeling flow chart is shown in Fig. 8. The NCEP data is used to initialize the mesoscale model (RAMS), which provide the velocity field as input to the dispersion model (HYPACT).

5.2. Pollutant Sources

Emission rates from the ground pollutant sources (industrial and residential) were measured such as SO_2, NOx, CO, TSP, etc.. RAMS/HYPACT is integrated from Dec 1, 2000 with the observational pollutant sources to Dec 31, 2000 (Fig. 9).

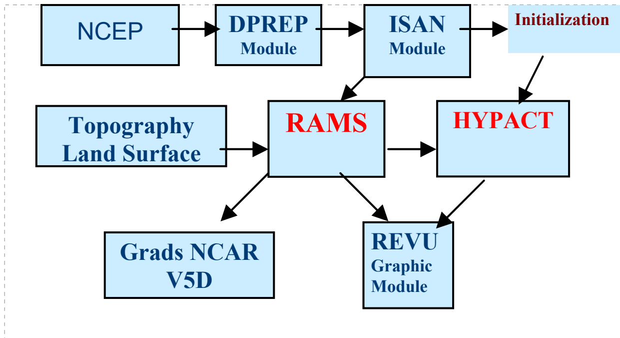

Fig. 8. RAMS/HYPACT modeling flow chart.

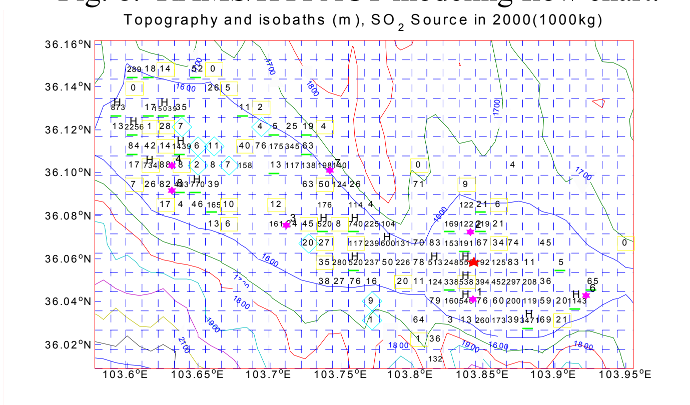

Fig. 9. SO_2 sources.

5.3. Model Verification

During the prediction period (Dec 1-31, 2000), eight observations of SO_2 were conducted on Dec 25, 2000. Except station-1, the predicted and observed SO2 concentrations agree with each other quite well (Fig. 10).

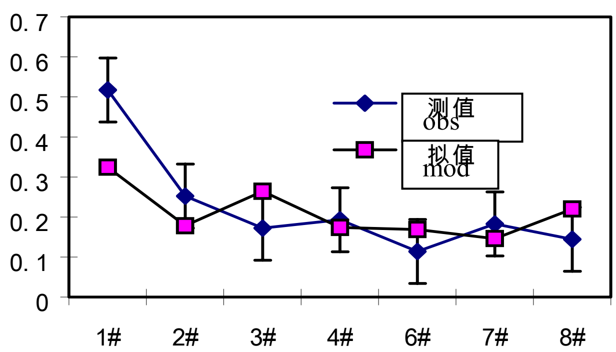

Fig. 10. RAMS/HYPACT model verification. The horizontal axis represents station number, and the vertical axis represents observed and predicted SO_2 concentration (unit: mg/m^3).

5.4. Predicted Temporal and Spatial Variability of Air-Pollutants

The RAMS/HYPACT model predicts the air-pollutant concentrations. Here, we show an NOx spreading event from 07h Dec 11 to 07h Dec 12, 2000 as an illustration. Two NOx plumes (concentration > 0.1 mg/m^3) occur at 07h Dec11. On Dec 11, the atmosphere has weak stratification. The plumes disperse to high altitudes. In the morning of Dec 12 (07 h), the stratification strengthens. The two plumes spread horizontally in the valley and cause high NOx concentration.

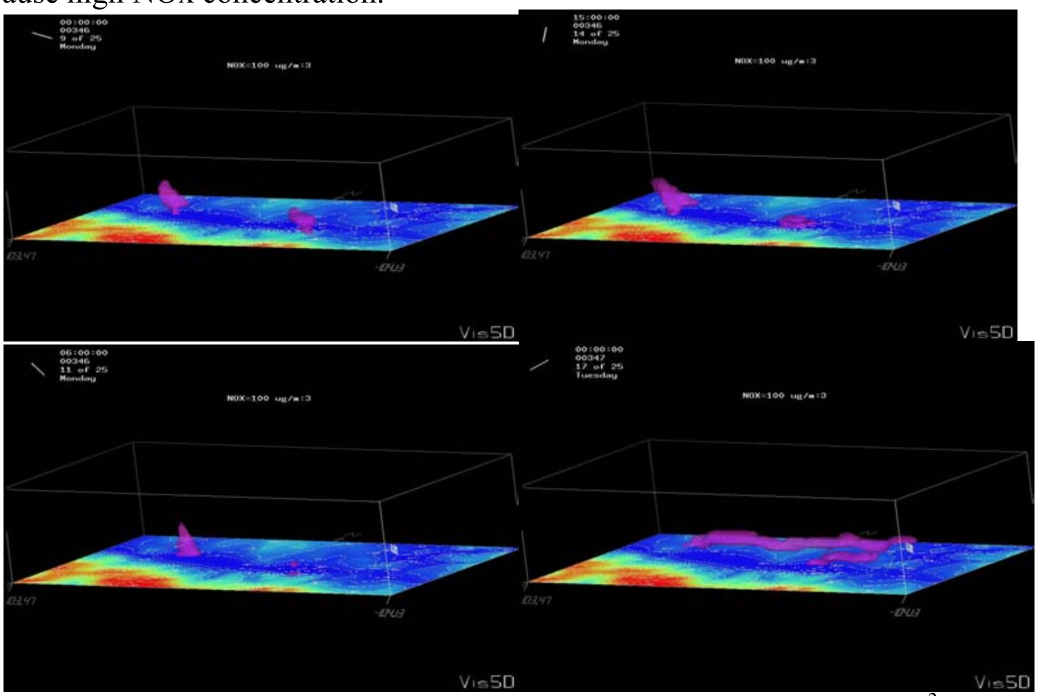

Fig. 11. Temporal variation of NOx plumes (concentration > 0.1 mg/m^3): (a) 7 h, Dec 11, (b) 13h, Dec 11, (c) 22h, Dec 11, and (d) 7h, Dec 12, 2000.

6. CONCLUSIONS

This study shows that the mountain-slope afforestation improves the air quality through destabilizing the atmosphere, enhancing the upward motion over the valley, and providing sinks for pollutants. Besides, the RAMS-HYPACT model has capability to predict the transport of pollutants.

ACKNOWLEDGEMENTS

This work was jointly supported by the National Natural Science Foundation of China Major Programs No. 40305020, and the Naval Postgraduate School. The data for this study are provided by the program entitled “Air Pollution and Control in Lanzhou”

jointly sponsored by the local government of Gansu Province and the Chinese Academy of Science.

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